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**DIGITAL HOLOGRAPHIC SPRAY
ANALYZER**



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| 14. ABSTRACT Advanced spray diagnostics are needed for studying the formation of drops in a variety of natural and technological spray processes, e.g. water falls, bow waves of ships, and many types of commercial spray atomizers, among others. Of interest is the dense-spray near-injector region which is typically opaque for spray diagnostics such as phase Doppler particle analyzers (PDPA). This is unfortunate because primary breakup processes that control spray size and velocity distributions occur in this optically challenging region. The present setup; digital holographic spray analyzer, allows the probing of dense spray regions and provides the user with droplet sizes and velocities measurements in three dimensions. The setup is based on typical in-line holography except that the holographic film is replaced with a CCD sensor. The actual process of capturing the hologram is a relatively simple process only requiring a laser, optics to form a collimated beam, and a digital camera. The hologram is then stored digitally and reconstructed numerically with a reconstruction program. | | | | | | |
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DIGITAL HOLOGRAPHIC SPRAY ANALYZER

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ABSTRACT

Advanced spray diagnostics are needed for studying the formation of drops in a variety of natural and technological spray processes, e.g. water falls, bow waves of ships, and many types of commercial spray atomizers, among others. Of interest is the dense-spray near-injector region which is typically opaque for spray diagnostics such as phase Doppler particle analyzers (PDPA). This is unfortunate because primary breakup processes that control spray size and velocity distributions occur in this optically challenging region.

The present setup; digital holographic spray analyzer, allows the probing of dense spray regions and provides the user with droplet sizes and velocities measurements in three dimensions. The setup is based on typical in-line holography except that the holographic film is replaced with a CCD sensor. The actual process of capturing the hologram is a relatively simple process only requiring a laser, optics to form a collimated beam, and a digital camera. The hologram is then stored digitally and reconstructed numerically with a reconstruction program. After reconstructing the hologram in many different planes, the droplet size distribution is measured. In addition droplet velocities are measured by means of double pulsed exposure configuration and PIV program. All these processes can be automated which is the strength of this technique. The output is a three dimensional map of droplets locations, sizes, and velocities.

This digital holographic spray analyzer was tested by measuring droplet sizes inside the dense spray created by an aerated injector subjected to a subsonic crossflow typical of test condition encountered in ramjet engine.

INTRODUCTION

Improved spray diagnostics are needed to better understand the formation of drops in many different applications ranging from combustion to agriculture to natural processes such as waterfalls. Of particular interest are very dense sprays that are inaccessible to other techniques such as phase Doppler particle analyzers (PDPA). For injectors this dense region occurs in the near injector area, and this is where the primary breakup processes that control droplet size and distribution downstream occur.

Traditional in-line holography has long been used for 3-D measurements in particle fields such as sprays [1-5]. With the advent of digital holography, this technique has become more popular [6, 7] since the costly holographic film and hazardous chemical development processes has been eliminated. Also, much work has gone into digital holographic PIV now that the holograms may be recorded and reconstructed digitally⁸⁻¹¹. Many of the same problems and solutions encountered in holographic PIV may be used in analyzing sprays with digital holography since both are trying to resolve small particles and compute velocities for these particles. The difference between the two; however, is that in spray applications the particle (droplets and ligaments) sizes and shapes differ at each location unlike holographic PIV where all particles are spherical and have one size.

In-line digital holography is a good candidate for particle fields because it greatly simplifies the optical setup compared to off-axis setup, and it is still able to resolve particle diameters and locations over three dimensions. Also the in-line configuration reduces the spatial resolution requirements for the CCD sensor, which has an order of magnitude lower resolution when compared with holographic emulsions.

When the hologram has been stored digitally the rest of the work is computationally. First, the image is numerically reconstructed which results in many images that represent 2-D "slices" of the volume focused at different distances. Then when a focused droplet is found the size and location is measured.

By incorporating a double pulsed setup where two holograms are taken a short time apart, the droplet's locations can be tracked across the two frames and the velocities of the individual droplets can be measured. The final output is a three dimensional map of droplet sizes and velocities.

Nomenclature

| | |
|------------|--|
| GLR | = aerating gas-to-liquid mass ratio |
| d_0 | = injector orifice diameter |
| m | = mass flow rate |
| q | = jet/freestream momentum flux ratio, $\rho_L v_j^2 / \rho_\infty u_\infty^2$ |
| SMD | = sauter mean diameter, $\sum d_i^3 / \sum d_i^2$, i for all droplets |
| u | = velocity component in the crossflow direction |
| v | = velocity component in jet streamwise direction |
| x | = crosstream distance |
| y | = streamwise distance |
| Subscripts | |
| j | = jet exit property |
| ∞ | = ambient gas property |

Experimental Methods

Apparatus

The liquid breakup experiments were carried out in a subsonic wind tunnel with a test section of 0.3 m x 0.3 m x 0.6 m. The wind tunnel had glass side walls, floor, and acrylic ceiling to provide optical access. Possible air crossflows were in the velocity range of 3-60 m/s at normal temperature and pressure. The wind tunnel had a contraction ratio > 16:1 and the velocity variation inside the test section was $< \pm 1\%$ of mean free-stream velocity. The test liquid was contained within a cylindrical liquid supply chamber having a diameter of 100 mm and a length of 300 mm, constructed of type 304 stainless steel.

Aerated-liquid injectors with exit diameters of 0.5 mm and 1.0 mm were used. These injectors consist of an inner tube for the aerating gas and an outer tube for the liquid, as shown in fig. 1. The aerating gas travels through the inner tube and passes through several 100 μ m holes located near the end of the tube. At sufficient GLRs the gas and liquid mix to form a two-phase flow which consists of a gas core surrounded by a thin liquid sheet (annular regime).

The liquid portion was forced through the nozzle by admitting high-pressure air to the top of the chamber. The air and liquid flowrates were then controlled by rotameter type flowmeters. The high-pressure air was kept in a storage tank with a volume of 0.18 m³ and had an air pressure limit up to 5000 kPa.

Instrumentation

The optical setup consisted of two frequency doubled YAG lasers (Spectra Physics Model LAB-150, 532 nm wavelength, 7 ns pulse duration, and up to 300 mJ optical energy per pulse) which could be fired with pulse separations as small as 100 ns. The beams were combined using a polarized beam splitter cube and the intensity was controlled by half wave plates that changed the direction of polarization. The beam then passed through another polarized beam splitter cube, which only allows either the horizontal or vertical portion of polarized light to pass through while the other portion is reflected and directed to a beam dump. This combination of half wave plates and beam splitter cubes controls the intensity of the beam. The beam was then collimated using a 20x objective lens and a 3 inch diameter convex lens with a focal length of 150 mm. This collimated beam then passed through the test section and fell directly on the CCD (Fig. 2). Any magnification was introduced by using a convex lens with a focal length of 300mm as relay lens after the test section, and then capturing a hologram of the magnified image (Fig. 3).

The holograms were captured on a Cooke Corporation cooled interline transfer CCD camera having 2048 x 2048 pixels that were 7.4 μ m wide by 7.4 μ m tall. All holograms and 2-D images were analyzed using MATLAB® combined with the optional image processing toolbox.

Test Conditions

The aerated injectors were tested at an 8% GLR. The gas used was air pressurized to 160 psi and the liquid used was water also pressurized to 160 psi. At this pressure and GLR, the v_j was measured by using double pulsed holography at the exit of the jet. The ligaments and drops were then tracked across the two frames and the surface velocity was found to be 24 m/s for the injector with $d_0 = 1.0$ mm and 23 m/s for $d_0 = 0.5$ mm. Using this jet velocity, the injectors were tested in a crossflow of $u_\infty = 65$ m/s which resulted in a $q = 93.5$ for the $d_0 = 1.0$ mm injector and a $q = 83.6$ for the $d_0 = 0.5$ mm injector. At these momentum flux ratios, holograms were taken at 50 injector diameters downstream of the injector. The droplets in the spray volume were then measured and represented by the SMD.

This technique was tested on the dense spray created by an aerated injector. The near injector area (<50 injector diameters downstream) is occupied by a very dense spray that is inaccessible with other methods such as phase Doppler particle anemometry (PDPA). The less dense area downstream has been measured using PDPA by Lin et al. [12,13], but the near injector region where the primary breakup is occurring has proved to be too dense for PDPA.

RESULTS AND DISCUSSION

Hologram Recording and Reconstruction

The single collimated beam setup was chosen over other possible holographic recording methods because of its simplicity and its favorability to digital recording. The inline arrangement reduces the spatial resolution requirements on the

CCD sensor which has a much lower resolution than traditional holographic film. The interference of the object and reference beam creates light and dark fringes, and according to the sampling theorem each fringe has to fall across two pixels to be resolved. The frequency of these fringes increases as the angle between the object and reference beam increase. Therefore, the in-line arrangement is the most suitable for the lower resolution CCD sensors.

In this single beam arrangement, the one beam acts as both reference and object beam. The portion of the beam that passes through the volume undiffracted serves as the reference beam. This eliminates the need to match the optical path lengths in order to stay within the coherence length of the laser.

The principle drawback with this single beam setup is that resolution decreases with density because there is not enough of the beam that passes through the volume unaffected by particles to serve as a reference beam. The Royer criterion [14] quantifies this amount of obscuration based on "shadow density." According to the Royer criterion, hologram quality can be defined by: a shadow density less than 1% produces a "good" hologram, between 1% and 10% produces a "marginal"-quality hologram, and greater than 10%, a "bad" hologram. Adding a separate reference beam solves the beam obscuration problem. However, to keep the low fringe frequency both the object and reference beam are combined with a beam splitter and sent to the CCD with in-line configuration.

This addition of a separate reference beam solves the problem of beam obscuration, but it does not solve all the problems associated with recording dense sprays. Another problem is intrinsic speckle noise. Meng et al. [15] describes this speckle noise as the interference of the scattering waves from multiple particles. When the scattered light waves interfere with each other, they appear as a random pattern of speckles when the hologram is reconstructed. This causes a problem with automatic particle measurement because it becomes difficult to distinguish a focused droplet from the speckles.

Meng et al. [15] offers two ways to improve this problem: 1) suppress the undiffracted reconstruction wave (a.k.a dc term) 2) Separate the virtual and real image through an off-axis setup. Schnars and Jüptner [16] offer two simple ways of suppressing this DC term: 1) subtract the average intensity from the hologram or 2) measure the intensities of the reference beam and object beam separately and subtract the intensities from the hologram before reconstruction. The method of average intensity subtraction is used in the current setup.

As for the virtual image issue, Meng and Hussain [17] provide a novel way for keeping the simplicity of the in-line recording configuration, and still have the benefits of off-axis reconstruction. However, this has only been done optically and to this author's knowledge has not been implemented digitally. The current setup neglects this out of focus virtual image because its effect is small enough that droplets can still be resolved and measured accurately.

After the hologram is recorded, it is reconstructed using a MATLAB program based on the convolution type approach

which solves the Rayleigh Sommerfeld formula for reconstruction of a wave field. This is done with the use of the Fast Fourier Transform algorithm. For more information on this method of reconstruction and other methods, the reader is referred to Kreis et al. [18]. This convolution method was chosen over the other popular and faster method using the Fresnel approximation because according to Kreis et al. [18], with the Fresnel approximation the reconstructed pixel size depends on the wavelength of the light and the reconstruction distance.

Drop Detection

The holograms were reconstructed at 5 mm increments through the spray volume. The reconstruction results in many planar images that represent 2-D "slices" through the spray volume. These images are then treated the same as any 2-D image with some droplets in focus and others that are not. These the individual frames are then manually examined to find focused droplets.

When a focused droplet is found a measurement program is used that automatically outlines the droplet and measures its dimensions. Droplet edge detection in these reconstructed holograms is difficult because the backgrounds of these focused images are generally very uneven due to other droplets at other planes that are out of focus. To correct these uneven backgrounds the average intensity of groups of pixels was taken and then subtracted from the original image. This left only the focused droplets with a much more uniform background. Then the edges of the droplets can be located and outlined. This outlining process uses an intensity gradient method that assumes the edge of the droplet is at the location of the largest intensity gradient.

The pixels in this outlined region are counted, and properties such as cross-sectional area and droplet diameter are calculated. Then by capturing another hologram of an object with known dimensions a correlation of distance per pixel can be made. The actual droplet diameter can be calculated.

When the droplet has been outlined, centroid location is also recorded. Using a double pulsed configuration where two holograms are taken a short time interval apart, these centroids can be tracked across the two frames and the velocity can be found. By applying the same techniques used in PIV, these centroids can automatically be tracked and the velocity for each droplet can automatically be found.

Application

This technique was applied to an aerated injector. This injector produces a dense spray of small droplets. The near injector region is an especially challenging environment because of the density of the spray. Measuring at a location 50 injector diameters downstream, droplets were resolved with an SMD of 18 μ m which coincides with the less than 20 μ m size suggested by Lin et al. [12] for the inner spray region.

The technique was also applied for flow visualization at the exit of the injector (Figs. 3-4). Figure 3 is a digitally captured hologram using the in-line technique described earlier. This hologram was taken at 2% GLR in still air. Figure 4 is the reconstruction of this hologram at 235 mm

away from the CCD sensor, which was the same distance from the injector to CCD in the recording setup. The annular two-phase flow can clearly be seen in this image. At the exit of the injector, the liquid and gas cores are still intact. The thin liquid sheet is then broken by the expanding gas inside.

Figure 5 is a reconstructed hologram taken at the injector exit. This spray results from an 8% GLR in a 65 m/s crossflow. The separation of the gas and liquid regions cannot be seen in this reconstruction because of the higher GLR which results in a much denser spray. It can be seen that the spray becomes very dense very quickly. In this inner region, the droplet density is very high which causes the measurement difficulties described earlier.

CONCLUSIONS

A digital holographic spray analyzer was developed that aids in 3-D spray visualization and measurement. This technique uses a single collimated beam for in-line recording and requires a relatively simple experimental setup with the majority of the work being done computationally.

For high particle densities, it was found that a separate reference beam was needed to solve the reference beam obscuration problem related to the single beam configuration. This does not solve all speckle noise problems but does improve resolution. For better improvement an off-axis setup is required with the expense of a more complicated experimental setup.

After the hologram has been reconstructed, droplet detection and measurement is done automatically, and the droplet diameter, SMD, and centroid location are recorded. The addition of double pulsed holography allows the calculation of velocity for each individual droplet. To automate this process, the cross-correlation techniques of PIV is applied.

This technique was applied to the dense near-injector area of an aerated injector. The droplet measurements coincided with work done by others on this injector. Overall, the technique was successful in this difficult environment.

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REFERENCES

- [1] J. D. Trolinger, R. A. Belz, and W. M. Farmer, "Holographic techniques for the study of dynamic particle fields," *Appl. Opt.*, Vol. 8, pp. 957-961, 1969.
- [2] R. Menzel and F. M. Shofner, "An investigation of Fraunhofer holography for velocimetry application," *Appl. Opt.*, Vol. 9, pp. 2073-2079, 1970.
- [3] B. J. Thompson, "Holographic particle sizing techniques," *J. Phys. E*, Vol. 7, pp. 781-788, 1974.
- [4] B. C. R. Ewan, "Particle velocity distribution measurement by holography," *Appl. Opt.*, Vol. 18, pp. 3156-3160, 1979.
- [5] B. C. R. Ewan, "Fraunhofer plane analysis of particle field holograms," *Appl. Opt.*, Vol. 19, pp. 1368-1372, 1980.
- [6] J. Burke, C. F. Hess, and V. Kebbel, "Digital Holography for Instantaneous Spray Diagnostics on a Plane," *Particle & Particle Systems Characterization*, Vol. 20, pp. 183-192, 2003.
- [7] S. L. Pu, D. Allano, B. Patte-Rouland, M. Malek, D. Lebrun, K. F. Cen, "Particle Field Characterization by Digital In-Line Holography: 3D Location and Sizing," *Exp. In Fluids*, Vol. 39, pp. 1-9, 2005.
- [8] P. J. Bryanston-Cross, M. Funes-Gallanzi, C. Quan, and T. R. Judge, "Holographic Particle Image Velocimetry (HPIV)," *Optics & Laser Technol.*, Vol. 5, pp. 251-256, 1992.
- [9] G. Pan and H. Meng, "Digital Holographic PIV for 3D Flow Measurement," *ASME Paper No. IMECE2002-33173, ASME International Mechanical Engineering Congress & Exposition*, New Orleans, Louisiana, Nov 2002.
- [10] K. D. Hinsch, "Holographic Particle Image Velocimetry," *Meas. Sci. Technol.*, Vol. 13, pp. 61-72, 2002.
- [11] H. Meng, G. Pan, Y. Pu, and S. H. Woodward, "Holographic Particle Image Velocimetry: from Film to Digital Recording," *Meas. Sci. Technol.*, pp. 673-685, 2004.
- [12] K.-C. Lin, P. J. Kennedy, and T. A. Jackson, "Spray Structures of Aerated-Liquid Jets in Subsonic Crossflows," *AIAA paper No. 2001-3178, 32nd AIAA Aerospace Sciences Meeting*, Reno, Nevada, 2001.
- [13] K.-C. Lin, Kennedy P. J., and Jackson, T. A., "Structures of Aerated-Liquid Jets in High-Speed Crossflows," *AIAA paper No. 2002-3178, 32nd AIAA Fluid Dynamics Conference*, St. Louis, Missouri, June 2002.
- [14] A. R. Jones, M. Sarjeant, C. R. Davis, and R. O. Denham, "Application of in-line holography to drop size measurement in dense fuel sprays," *Appl. Opt.*, Vol. 17, pp. 328-330, 1978.
- [15] H. Meng, W. L. Anderson, F. Hussain, and D. Liu, "Intrinsic speckle noise in in-line particle holography," *J. Opt. Soc. Am.*, Vol. 10, pp. 2046-2058, 1993.
- [16] U. Schnars and W. Jüptner, *Digital Holography: Digital Hologram Recording, Numerical Reconstruction, and Related Techniques*, Springer, 2005.
- [17] H. Meng and F. Hussain, "In-Line Recording and Off-Axis Viewing Technique for Holographic Particle Velocimetry," *Appl. Opt.*, Vol. 34, pp. 1827-1840, 1995.
- [18] T. Kreis, M. Adams, and W. Jüptner, "Methods of Digital Holography: A Comparison," *SPIE*, Vol. 3098, pp. 224-233, 1997.

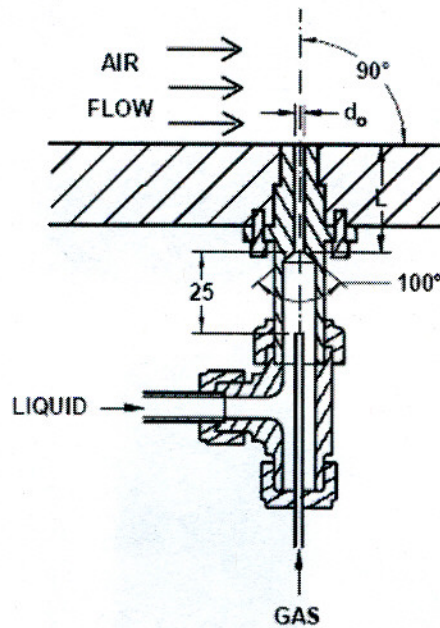


Fig. 1 Schematic of the Injector Assembly.

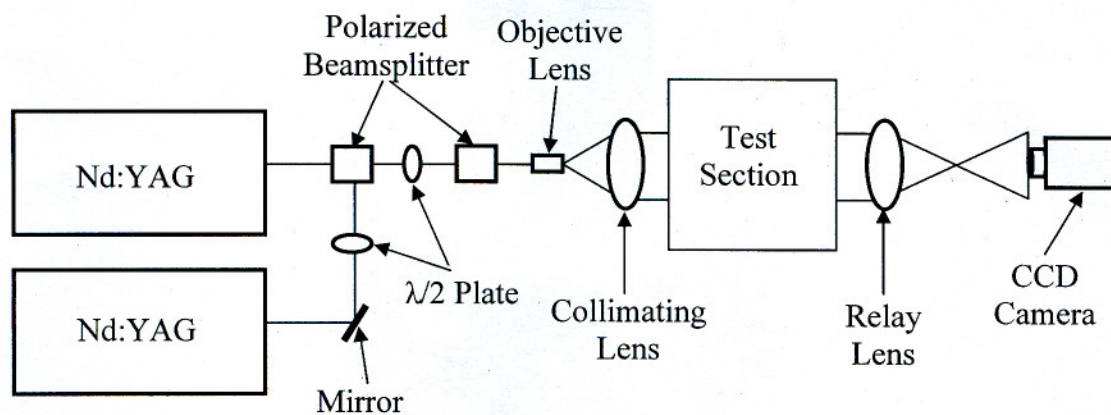


Fig. 2 Optical Setup Using Single Beam as Reference- and Object-Beam.



Fig. 3 Digitally Captured Hologram of Aerated Jet at 2% GLR in Still Air.

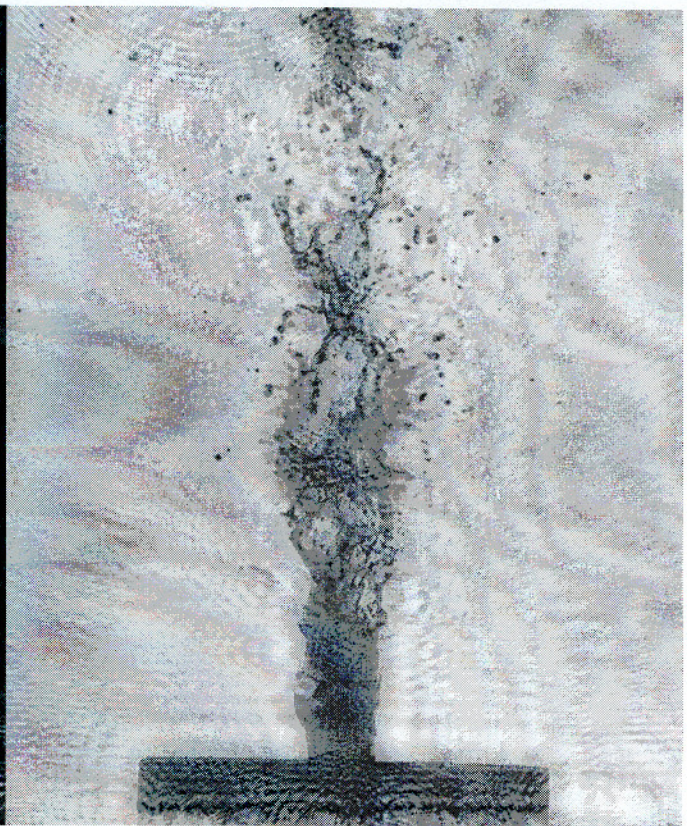


Fig. 4 Reconstructed Hologram of Aerated Jet at 2% GLR in Still Air.

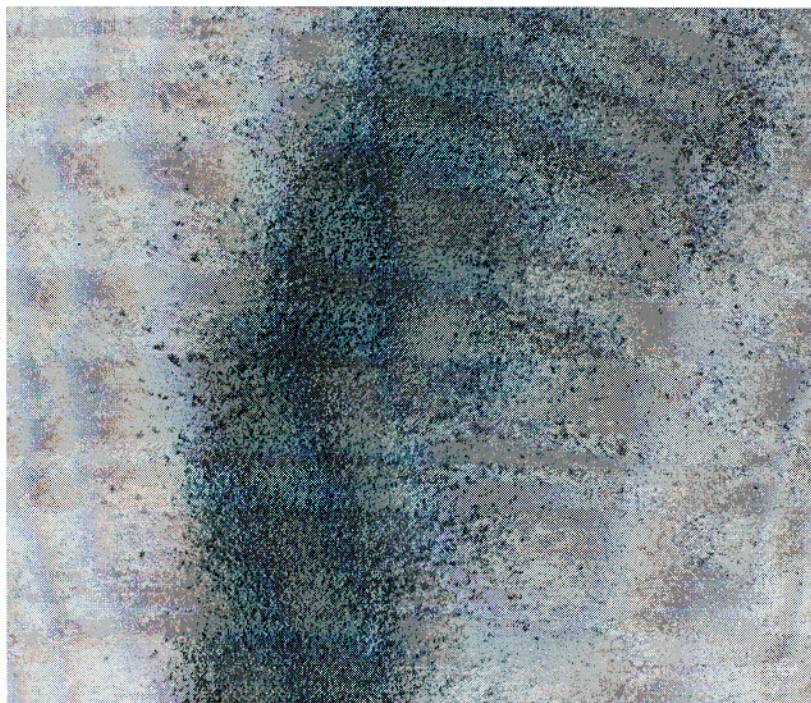


Fig. 5 Reconstructed Hologram of Aerated Jet at 8% GLR in $M=0.27$ Crossflow.